JC04 Rec'd PCT/PTO 15 JUN 2001

FORM PTO-1390 (REV. 11-2000) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY'S DOCKET NUMBER: 09794353-0016

U.S. APPLICATION NO. (If known, see 37 CFR 1.5): 09/868360

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/JP00/07182	17 October 2000	20 October 1999

TITLE OF INVENTION: SEE ATTACHMENT

APPLICANT(S) FOR DO/EO/US

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. [X] This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. [ ] This is a **SECOND or SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. [X] This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. [ ] The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. [X] A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. [X] is attached hereto (required only if not communicated by the International Bureau).
   b. [ ] has been communicated by the International Bureau.
   c. [ ] is not required, as the application was filed in the United States Receiving Office (RO/US).
6. [X] An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
   a. [X] is attached hereto.
   b. [ ] has been previously submitted under 35 U.S.C. 154(d)(4).
7. [X] Amendments to the claims of the International Aplication under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. [ ] are attached hereto (required only if not communicated by the International Bureau).
   b. [ ] have been communicated by the International Bureau.
   c. [ ] have not been made; however, the time limit for making such amendments has NOT expired.
   d. [X] have not been made and will not be made.
8. [ ] An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371 (c)(3)).
9. [ ] An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. [ ] An English lanugage translation of the annexes of the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 20 below concern document(s) or information included:

11. [X] An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. [ ] An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. [X] A FIRST preliminary amendment.
14. [ ] A SECOND or SUBSEQUENT preliminary amendment.
15. [ ] A substitute specification.
16. [ ] A change of power of attorney and/or address letter.
17. [ ] A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
18. [ ] A second copy of the published international application under 35 U.S.C. 154(d)(4).
19. [ ] A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
20. [X] Other items or information:

Express Mail Label No: EL281568418US
Attachment

371 Rec'd PCT/PTO 15 JUN 2001

U.S. APPLICATION NO (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO	ATTORNEY'S DOCKET NUMBER
09/868560	PCT/JP00/07182	09794353-0016

21. ☒ The following fees are submitted:	CALCULATIONS PTO USE ONLY	
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)):		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a (2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1000.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$860.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$710.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$690.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 860.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	-36 -20 =	16	x **$18.00**	$ 288.00	
Independent claims	17 -3 =	14	x **$80.00**	$ 1,120.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$	
TOTAL OF ABOVE CALCULATIONS =				$ 2,268.00	
☐ Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.			+	$ 0.00	
SUBTOTAL =				$	
Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				$	
TOTAL NATIONAL FEE =				$ 2,268.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$ 0.00	
TOTAL FEES ENCLOSED =				$	
				Amount to be refunded:	$
				charged:	$

a. ☒ A check in the amount of $ $2,268.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. _____ in the amount of $ _____ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 19-3140 . A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.

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David R. Metzger
NAME

32,919
REGISTRATION NUMBER

20 DEC 01 09868560

09/868360

ATTACHMENT JC13 Rec'd PCT/PTO 15 JUN 2001

TITLE: **CONTROL METHOD OF PHASE TRANSITION OF FRACTAL-COUPLED STRUCTURE, FRACTAL-COUPLED STRUCTURE, FERROMAGNETIC FRACTAL-COUPLED STRUCTURE, INFORMATION PROCESSING METHOD, INFORMATION STORAGE METHOD, INFORMATION STORAGE MEDIUM, INFORMATION PROCESSING DEVICE AND INFORMATION STORAGE DEVICE**

09868360 "010302

09/868360
JC18 Rec'd PCT/PTO 15 JUN 2001

IN THE UNITED STATES ELECTED OFFICE
OF THE UNITED STATES PATENT AND TRADEMARK OFFICE
UNDER THE PATENT COOPERATION TREATY-CHAPTER II

PRELIMINARY AMENDMENT

APPLICANT(S): Ryuichi Ugajin, et al. ATTORNEYS DOCKET NO: 09794353-0016

SERIAL NO:

Filed:

INTERNATIONAL APPLICATION NO: PCT/JP00/07182

INTERNATIONAL FILING DATE: 17 October 2000

TITLE: CONTROL METHOD OF PHASE TRANSITION OF FRACTAL-COUPLED STRUCTURE, FRACTAL-COUPLED STRUCTURE, FERROMAGNETIC FRACTAL-COUPLED STRUCTURE, INFORMATION PROCESSING METHOD, INFORMATION STORAGE METHOD, INFORMATION STORAGE MEDIUM, INFORMATION PROCESSING DEVICE AND INFORMATION STORAGE DEVICE

Hon. Assistant Commissioner for Patents
Washington, D.C. 20231

SIR:

Please amend the above-identified International Application before entry into the national stage at the U.S. Patent and Trademark Office as follows.

IN THE SPECIFICATION:

Please amend the specification as follows:

On page 1, line 1 delete "DESCRIPTION" and insert

--TITLE--

On page 1, line 9 add

--BACKGROUND OF THE INVENTION --

On page 1, line 10 delete "Technical Field" and insert

--FIELD OF THE INVENTION--

At page 6, line 21 delete "Disclosure of Invention" and insert

--SUMMARY OF THE INVENTION--

At page 17, line 5, delete "Best Mode For Carrying Out the Invention" and insert

--DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS--

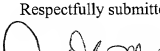
At page 35, line 1, after "Claims" insert

--WHAT IS CLAIMED IS--

REMARKS

The foregoing Preliminary Amendment is made to place the specification into U.S. format. No new matter has been added. Applicants look forward to early and favorable action by the Examiner.

Respectfully submitted,



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29/PRTS

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DESCRIPTION

CONTROL METHOD OF PHASE TRANSITION OF FRACTAL-COUPLED STRUCTURE, FRACTAL-COUPLED STRUCTURE, FERROMAGNETIC FRACTAL-COUPLED STRUCTURE, INFORMATION PROCESSING METHOD, INFORMATION STORAGE METHOD, INFORMATION STORAGE MEDIUM, INFORMATION PROCESSING DEVICE AND INFORMATION STORAGE DEVICE

PCT/JP00/01302 09868360

Technical Field

This invention relates to a control method of phase transition of fractal-coupled structures, fractal-coupled structures, ferromagnetic fractal-coupled structures, information processing method, information storage method, information storage medium, information processing device and information storage device, which, in particular, are based on a new principle.

Background Art

Materials exhibiting ferromagnetism are widely used as storage mediums, and support present technologies. Not only bulk magnetic materials but also those variously designed in layered structures are used, and they are employed in, for example, magneto-optical discs (MO discs). There are also vigorous researches and developments toward future magnetic materials, and in recent years, powder magnetic materials, i.e. magnetic particles, have been remarked ((1) J.M. L. Billas, A. Chatelain, W.A. de Heer,

Science, 265, 1682(1994), (2) D. Gatteschi, A. Caneschi, L. Pardi and R. Sessoli, Science, 265, 1054(1994)).

On the other hand, inherent non-linearity is indispensable as a physical system assuming information processing. Although linearly responsive ones are also used as devices, they cannot be active devices. As devices used conventionally, there are electronic devices using materials that exhibit non-linear responses to a certain extent. For example, two-terminal devices exhibiting differential negative resistance are an example of those having non-linearity in current-voltage characteristics. Of course, three-terminal MOS-FETs also support the present techniques. Then, by coupling these electronic devices having non-linearity with linear electronic circuits and thereby building an information processing apparatus having non-linearity, any desired calculation can be performed.

However, difficulties by high integration have become issues with such electronic circuits. Heating is one of such problems. Heating caused by inherent electric resistance is indispensable for creating non-linearity of an electronic device, indispensable for executing information processing, and therefore essential.

In order to overcome the difficulty, trials have been made to decrease devices by enhancing non-linearity of components elements. Progress of this scheme necessarily leads to the demand for component devices having as strong non-linearity as exhibiting a chaos. When a

classical system exhibiting a chaos is quantized, what characterizes the behaviors of the quantum system is a quantum chaos.

On the other hand, as a component device is minimized more and more, electrons confined in the device will behave as quantum-mechanic particles. Therefore, from this viewpoint, hopes are placed on component devices exhibiting a chaos.

For application of a solid material to electronic or optical devices, physical properties of the material may restrict its applications. For example, in case of using a semiconductor material in a light emitting device, it will be usable in a device of an emission wavelength corresponding to the band gap of the material, but some consideration will be necessary for changing the emission wavelength. Regarding physical properties related to semiconductor bands, controls by superlattices have been realized. More specifically, by changing the period of a superlattice, the band width of its subband can be controlled to design an emission wavelength.

Targeting on controlling many-electron-state structures by material designs, the Inventors proposed many-body effect engineering by quantum dot coupled structures and has continued theoretical analyses ((3) U.S. Patent 5,430,309; (4) U.S. Patent 5,663,571; (5)U.S. Patent 5,719,407; (6) U.S. Patent 5,828,090; (7) U.S. Patent 5,831,294; (8) J. Appl. Phys. 76, 2833(1994); (9) Phys. Rev.

20020107.0523850

B51, 10714(1995); (10) Phys. Rev. B51, 11136(1995); (11) J. Appl. Phys. 77, 5509(1995); (12) Phys. Rev. B53, 6963(1996); (13) Phys. Rev. B53, 10141(1996); (14) Appl. Phys. Lett. 68, 2657(1996); (15) J. Appl. Phys. 80, 3893(1996); (16) J. Phys. Soc. Jpn. 65, 3952(1996); (17) Jpn. J. Appl. Phys. 36, 638(1997); (18) J. Phys. Soc. Jpn. 66, 425(1997); (19) Jpn. J. Appl. Phys. 81, 2693(1997); (20) Physica (Amsterdam) 229B, 146(1997); (21) Physica (Amsterdam) 237A, 220(1997); (22) Surf. Sci. 375, 403(1997); (23) Physica (Amsterdam) 240B, 116(1997); (24) Physica (Amsterdam) 240B, 128(1997); (25) Physica (Amsterdam) 1E, 226(1997); (26) Phys. Rev. Lett. 80, 572(1998); (27) Jpn. J. Appl. Phys. 37, 863(1998); (28) Physica (Amsterdam) 245B, 311(1998); (29) Physica (Amsterdam) 235B, 96(1998); (30) Phys. Rev. B59, 4952(1999); (31) Surf. Sci. 432, 1(1999); (32) International Journal of Modern Physics B. Vol. 13, No. 21, 22, pp.2689-2703, 1999). For example, realization of various correlated electronic systems is expected by adjusting a tunneling phenomenon between quantum dots and interaction between electrons. Let the tunneling transfer between adjacent quantum dots be written as t. Then, if quantum dots are aligned in form of a square lattice, the band width of one electron state is $T_{eff}=4t$. If quantum dots form a one-dimensional chain, the band width of one electron state is $T_{eff}=2t$. In case of a three-dimensional quantum dot array, $T_{eff}=6t$. That is, if D is the dimension of a quantum dot array, the band width of one electron state has been

$T_{eff}=2Dt$.

When a magnetic material is used in a storage medium, it may be necessary to heat it high above the temperature of its ferromagnetic phase transition for, for example, erasure of storage, and this is a constraint on its applications. Therefore, if the ferromagnetic phase transition temperature can be controlled by changing some parameter without heating, the possibility of various technical applications will be extended.

On the other hand, regarding devices using a quantum chaos, it is known that degeneracy in density of states occurs due to the self-similarity in a quantum system having a fractal structure. Although this itself is useful, the quantum chaos the system exhibits is defined by GOE (Gaussian orthogonal ensemble) distribution, it is relatively weak in terms of quantum chaos. Thus there is a demand for realization of a stronger quantum chaos.

Further, consideration is made about half-filled (one electron per each quantum dot) Mott transition (also called Mott-Hubbard transition or Mott metal-insulator transition). Let the effective electrons interaction within a quantum dot be written as U_{eff}, then the Hubbard gap on the part of the Mott insulator is substantially described as $\Delta=U_{eff}-T_{eff}$, and the Mott transition can be controlled by changing U_{eff} or t. As already proposed, the Mott-Hubbard transition can be controlled by adjusting U_{eff} or t, using a field effect, it is applicable to field effect

devices (References (7), (8), (13) and (16) introduced above). However, if the Mott-Hubbard transition can be controlled by controlling a parameter other than the field effect, it is more advantageous for increasing the possibility of its applications.

It is therefore an object of the invention to provide a method of controlling phase transition of a fractal-coupled structure, which can control phase transition such as ferromagnetic phase transition without the need for heating, unlike the conventional techniques.

Another object of the invention is to provide a fractal-coupled structure and a ferromagnetic fractal-coupled structure in which the above-indicated control method can be used.

A further object of the invention is to provide an information processing method, information storage method, information storage medium, information processing device and information storage device that use the above-mentioned control method or fractal-coupled structure.

Disclosure of Invention

The Inventors found, through concentrated researches toward solution of those issues, that in a system using a fractal-coupled structure the fractal dimension is closely related to occurrence of phase transition, and the phase transition can be controlled by controlling the fractal dimension. The phase transition includes various kinds of

transition, such as ferromagnetic phase transition, Mott-Hubbard transition, Anderson transition via generation of a quantum chaos, and so forth. The phase transition can be used in information storage, and more generally in information processing, by the phase state before phase transition to information.

The present invention has been made as a result of further researches from various other viewpoints based on the former researched by the Inventor.

According to the first aspect of the invention, there is provided a method for controlling phase transition of a fractal-coupled structure characterized in controlling phase transition by controlling fractal dimension of a fractal-coupled structure overall or locally.

In the first aspect of the invention, if phase transition by a change in temperature is used, phase transition temperature is controlled by controlling fractal dimension of the fractal-coupled structure. Especially when the fractal-coupled structure is a ferromagnetic fractal-coupled structure, ferromagnetic phase transition temperature is controlled by controlling fractal dimension of the ferromagnetic fractal-coupled structure. In the ferromagnetic fractal-magnetic structure, a remarkable change in phase transition temperature can be obtained when the fractal dimension is not smaller than 2.5.

Alternatively, generation of quantum chaos in the fractal-coupled structure may be controlled by controlling

the fractal dimension of the fractal-coupled structure, and through it, Anderson (local) transition may be controlled. This is applicable to a fractal-coupled structure to which a magnetic impurity is added.

Phase transition may be metal-insulator transition, which is suitable for a fractal-coupled structure controlled to have a half-filled electron density. Usable as this type of fractal-coupled structure is one composed of a quantum dot array, made of, for example, heterojunction of compound semiconductors.

According to the second aspect of the invention, there is provided a ferromagnetic fractal-coupled structure characterized in comprising a magnetic material configured to have self-similarity.

In the second aspect of the invention, ferromagnetic phase transition temperature is typically determined by selecting a fractal dimension that characterizes self-similarity of a magnetic material. Especially for obtaining a drastic change in phase transition temperature, fractal dimension of the magnetic material is adjusted to not smaller than 2.5. The magnetic material takes the form of, for example, magnetic particles or magnetic atoms. The features explained above with reference to the first aspect of the invention may be applied here again unless they are incompatible.

According to the third aspect of the invention, there is provided a fractal-coupled structure characterized

in being configured to have self-similarity and being applied with random magnetic fields.

In the third aspect of the invention, random fields are typically applied by addition of magnetic impurities in its component material. The random magnetic fields are introduced to allow both realization of stronger quantum chaos by the effect of the magnetic fields and self-similarity the fractal configuration has. In the fractal-coupled structure added with the magnetic impurity, self-similar strong-coupled quantum chaos can be realized.

According to the fourth aspect of the invention, there is provided a fractal-coupled structure characterized in being configured to have self-similarity and having a half-filled electron density.

In the fourth aspect of the invention, interaction of electrons typically in an electron system can be made larger than the band width, and Mott metal-insulator transition exists, which is controlled by fractal dimension of the system. This fractal-coupled structure can be composed of a quantum dot array made of, for example, heterojunction of compound semiconductors. This type of fractal-coupled structure can be used to construct, for example, a semiconductor device or an electronic device.

According to the fifth aspect of the invention, there is provided an information processing method characterized in executing information processing by controlling phase transition through overall or local

control of fractal dimension of a fractal-coupled structure.

According to the sixth aspect of the invention, there is provided an information storage method characterized in performing information storage by controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

According to the seventh aspect of the invention, there is provided an information storage medium using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity.

According to the eighth aspect of the invention, there is provided an information storage medium using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields.

In the eighth aspect of the invention, information can be stored by using coexistence of degeneracy of density of states caused by the self-similarity and a strong quantum chaotic state, which appear in the fractal-coupled structure.

According to the ninth aspect of the invention, there is provided an information storage medium characterized in using a fractal-coupled structure which is configured to have self-similarity and has a half-filled electron density.

According to the tenth aspect of the invention, there is provided an information processing device characterized in executing information processing by

controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

According to the eleventh aspect of the invention, there is provided an information processing device characterized in:

using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity; and

executing information processing by controlling phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

According to the twelfth aspect of the invention, there is provided an information processing device characterized in:

using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields; and

executing information processing by controlling phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

According to the thirteenth aspect of the invention, there is provided an information processing device characterized in:

using a fractal-coupled structure configured to have self-similarity and having a half-filled electron state; and

executing information processing by controlling

phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

According to the fourteenth aspect of the invention, there is provided an information storage device characterized in executing information storage by controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

According to the fifteenth aspect of the invention, there is provided an information storage device characterized in:

using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity; and

executing information storage by controlling phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

According to the sixteenth aspect of the invention, there is provided an information storage device characterized in:

using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields; and

executing information storage by controlling phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

According to the seventeenth aspect of the invention, there is provided an information storage device

characterized in:

using a fractal-coupled structure configured to have self-similarity and having a half-filled electron density; and

executing information storage by controlling phase transition through overall or local control of fractal dimension of the fractal-coupled structure.

In the fifth to seventeenth aspects of the invention, the features explained above with reference to the first to fourth aspects of the invention may be applied unless they are incompatible.

According to the invention having any of the above-summarized constructions, phase transition of a fractal-coupled structure can be controlled by controlling fractal dimension without the need for heating that has been indispensable conventionally, and it can be used for execution of various kinds of information processing, including information storage.

Brief Description of Drawings

Fig. 1 is a schematic diagram that shows a fractal dimension Df obtained with a parameter α in a first embodiment of the invention;

Fig. 2 is a schematic diagram that shows a relation between temperature and magnetization of a two-dimensional on-disk Pott's model in the first embodiment of the invention;

Fig. 3 is a schematic diagram that shows a relation

between temperature and magnetization of an on-disk regular polyhedral model in the first embodiment of the invention;

Fig. 4 is a schematic diagram that shows a relation between temperature and magnetization of a three-dimensional on-ball Pott's model in the first embodiment of the invention;

Fig. 5 is a schematic diagram that shows a relation between temperature and magnetization of a three-dimensional on-ball regular polyhedral model in the first embodiment of the invention;

Fig. 6 is a schematic diagram that shows a relation between temperature and magnetization of an N=2 Ising model in the first embodiment of the invention;

Fig. 7 is a schematic diagram that shows a relation between temperature and magnetization of an N=6 Pott's model in the first embodiment of the invention;

Fig. 8 is a schematic diagram that shows a relation between temperature and magnetization of an N=12 Pott's model in the first embodiment of the invention;

Fig. 9 is a schematic diagram that shows a relation between temperature and magnetization of a regular octahedral model in the first embodiment of the invention;

Fig. 10 is a schematic diagram that shows a relation between temperature and magnetization of a regular icosahedral model in the first embodiment of the invention;

Fig. 11 is a schematic diagram that illustrates a specific example of the first embodiment of the invention;

Fig. 12 is a schematic diagram that shows a treelike fractal obtained by fractal growth of n=10000 under α=0 in a second embodiment of the invention;

Fig. 13 is a schematic diagram that shows a treelike fractal obtained by fractal growth of n=10000 under α=1 in the second embodiment of the invention;

Fig. 14 is a schematic diagram that shows a treelike fractal obtained by fractal growth of n=10000 under α=2 in the second embodiment of the invention;

Fig. 15 is a schematic diagram that shows a fractal dimension D_f obtained with a parameter α in the second embodiment of the invention;

Fig. 16 is a schematic diagram that shows a quantum level statistic under r=0 in the second embodiment of the invention;

Fig. 17 is a schematic diagram that shows a quantum level statistic under r=0 in the second embodiment of the invention;

Fig. 18 is a schematic diagram that shows a quantum level statistic under r=1 in the second embodiment of the invention;

Fig. 19 is a schematic diagram that shows a quantum level statistic under r=1 in the second embodiment of the invention;

Fig. 20 is a schematic diagram that shows changes in density of states obtained by a numerical calculation in a third embodiment of the invention;

Fig. 21 is a schematic diagram that shows, in an enlarged scale, a region proximate to the Mott-Hubbard gap shown in Fig. 20;

Fig. 22 is a schematic diagram that shows changes in density of states under t=1, n=10001 and α=1 all fixed, while changing U as 4, 8, 12 and 16, in a third embodiment of the invention;

Fig. 23 is a schematic diagram that shows changes in density of states under t=1, n=10001 and α=1 all fixed, while changing U as 2, 4, 8, 16 and 16, in the third embodiment of the invention;

Fig. 24 is a schematic diagram that shows changes in density of states under t=1, n=10001 and U=8 all fixed, while changing α as 0, 1 and 2 in the third embodiment of the invention;

Fig. 25 is a schematic diagram that shows changes in density of states under t=1, n=10001 and U=4 all fixed, while changing α as 0, 1 and 2 in the third embodiment of the invention;

Fig. 26 is a schematic diagram that shows changes in Hubbard gap under t=1 and n=10001 both fixed, while changing U continuously under α=0, 0.2, 0.4, 0.6, 1 and 2 in the third embodiment of the invention;

Fig. 27 is a schematic diagram that shows changes in density of states on Fermi energy under t=1 and n=10001 both fixed, while changing U continuously under α=0, 0.2, 0.4, 0.6, 1 and 2 in the third embodiment of the invention;

and

Figs. 28A and 28B are schematic diagrams that show a specific example of the third embodiment of the invention.

Best Mode for Carrying Out the Invention

Embodiments of the invention will now be explained below.

Explanation is started with the first embodiment of the invention. In the first embodiment, explanation will be made about controls of transition temperature by fractal dimension of a ferromagnetic fractal-coupled structure.

The ferromagnetic fractal-coupled structure is made by creating a fractal in the following manner and placing a spin thereon.

(1) Formation of a Fractal

First reviewed is a dielectric breakdown model ((33) A. Erzan, L. Pietronero, A. Vespignani, Rev. Mod. Phys. 67, 545(1995); (34) L. Niemeyer, L. Pietronero, H.J. Wiesmann, Phys. Rev. Lett. 52, 1033(1984)).

Let a square lattice S in a three-dimensional space be defined, and let a scalar potential field $\phi(i_1, i_2, i_3)$ be defined on lattice sites of the square lattice $(i_1, i_2, i_3) \in S$. Let it be called a potential and let the potential obey the Laplace equation

$$\Delta\phi(i_1,i_2,i_3)=0 \qquad (1)$$

A pattern T_n is a set of lattice sites on the three-dimensional lattice. T_0 contains (0, 0, 0) alone, and T_{n+1} is created by adding a single lattice site to T_n according to the rule give below.

Let the potential of each site contained in T_n be 1 and let the potential at infinity be 0. That is,

$$\phi(i_1,i_2,i_3)=0 \quad when \quad (i_1,i_2,i_3)\to\infty \tag{2}$$

$$\phi(i_1,i_2,i_3)=1 \quad when \quad (i_1,i_2,i_3)\in T_n \tag{3}$$

Under these boundary conditions, Equation (1) is solved to determine the potential. The lattice site which will be added to Tn to construct T_{n+1} is not contained in T_n, and it is selected from the set of lattice sites, i.e. U_n, nearest to T_n. The number of lattice sites contained in U_n is denoted by N_n.

Strength of the electric fields for lattice sites ($i_{1,m}$, $i_{2,m}$, $i_{3,m}$) (where m=1, 2, ..., N_n) in U_n is defined as

$$E_m(\alpha)=\left|\phi(i_{1,m},i_{2,m},i_{3,m})-1\right|^{\alpha} \tag{4}$$

The probability that a certain site ($i_{1,m}$, $i_{2,m}$, $i_{3,m}$) in U_n is selected is proportional to the electric field $E_m(\alpha)$. That is, the probability is

$$p_m(\alpha)=\frac{E_m(\alpha)}{\sum_{j=1}^{N_n}E_j(\alpha)} \tag{5}$$

By repeating these operations, construction of T_n is progressed. An ideal fractal will be a set of limits repeated infinitely as

$$T_\infty = \lim_{n\to\infty} T_n \tag{6}$$

When α=1, the foregoing and the result of generation of the pattern by Diffusion limited aggregation ((35) T.A. Witten, Jr. and L.M. Sander, Phys. Rev. Lett. 47, 1400(1984); Phys. Rev. B27, 5686(1983)). Fractal dimensions D_f of fractal patterns obtained by numerical simulation with various values of α are collectively shown in Fig. 1.

(2) Spin system on a Fractal

Let a spin system describing a ferromagnetic material be defined on the fractal defined in (1). Assume a lattice site shown below, which is the origin of T_n.

$$r_p = (i_{1,p} i_{2,p}, i_{3,p}) \in T_n \tag{7}$$

where p=1, 2, ..., n+1. By placing a spin on a lattice site $r_p \in T_n$, here is taken a spin system that can be described by the following Hamiltonian.

$$H = -\sum_{p,q} J_{p,q} S_p \cdot S_q \tag{8}$$

S_p is the spin at the p site. As spin-spin interaction $J_{p,q}$, a natural model is:

$$J_{p,q} = \begin{cases} 1 & when \quad |r_p - r_q| = 1 \\ 0 & otherwise \end{cases} \tag{9}$$

That is, spin-spin interaction exists only between nearest sites. For the purpose of calculating spontaneous magnetization M at a finite temperature T, statistical

mechanics of an equilibrium system is introduced. A partition function Z is defined as follows.

$$Z = \sum_{\{S_p\}} e^{-H/T} \qquad (10)$$

where $\{S_p\}$ in the symbol of the sum pertains to the sum regarding all spin states. Spontaneous magnetization is defined as the statistical average of spin as follows.

$$M = \frac{1}{n+1} \sum_{p=1}^{n+1} \langle S_p \rangle \qquad (11)$$

where the expected value $\langle S_p \rangle$ is

$$\langle S_p \rangle = \frac{1}{Z} \sum_{\{S_p\}} S_p e^{-H/T} \qquad (12)$$

and n+1 is the total number of spins. N is generally a vector quantity in a spin space, but its absolute value M=|M| is calculated.

A Pott's model is taken as the first example ((36) F.Y. Wu, Rev. Mod. Phys. 54, 235(1982)). This model uses as the spin

$$S_p = \left(\cos\frac{2\pi m_p}{N}, \sin\frac{2\pi m_p}{N} \right) \qquad (13)$$

where n_p=0, 1, 2, ..., N-1. In case of N=2, it is the same as an Ising model, and simulation is executed regarding N=2, N=6 and N=12. As a second example, those taking spin states at vertices of regular octahedrons and regular icosahedrons are taken for consideration. For these spin systems, spontaneous magnetization is calculated by using the Monte Carlo method. In the following example, 10000 Monte Carlo

steps were used. As fractals, those by 10000 steps of growth under each value of α, that is, fractals of n=10001, were used.

Prior to showing results about magnetism on fractals, here are shown results of calculation of spontaneous magnetization of normal two-dimensional and three-dimensional systems. As two-dimensional systems, those having 10001 sites in a disk-like arrangement were used. Fig. 2 shows the results of two-dimensional on-disk Pott's models. In case of an Ising model of N=2, transition temperature T_c is ~2.3. On the other hand, in models of N=6 and N=12, T_c is ~1.2. Fig. 3 shows results of regular polyhedral models. For reference, results of Ising models were shown together. T_c is ~1.0 in regular octahedral models, and T_c is ~0.7 in icosahedral models.

The review is now developed to three-dimensional systems. In this case, models placing 10001 sites in form of balls. Fig. 4 shows results of three-dimensional on-ball Pott's models. In case of an Ising model of N=2, T_c is ~4.2. In case of N=6 and N=12, T_c is ~2.1. Fig. 5 shows results of regular polyhedral models. For reference, results of Ising models were shown together. T_c is ~1.6 In regular octahedral models, and T_c is ~1.5 in regular icosahedral models.

A review is made on spontaneous magnetization on a spin system on a fractal-shaped structure, which is the issue in this section. Fig. 6 shows results of N=2 Ising

models. Fig. 7 shows results of Pott's models of N=6, and Fig. 8 shows those of N=12. Fig. 9 shows results of regular octahedral models, and Fig. 10 shows results of regular icosahedral models. The parameter α of fractals is changed from 0 to 0.4, 0.8, 1.2, 1.6 and 2. Fractal dimension is near 3 when α=0, then decreases gradually as α increases, and reaches approximately 2.1 under α=2. It will be appreciated that T_c decreases as α increases in any of the models. In case of Fig. 6, changes of T_c from ~4.1 to ~1.0 are observed in response to changes from α=0 to α=2. In case of Fig. 7, changes of T_c from ~2.1 to ~0.4 are observed in response to changes from α=0 to α=2. In case of Fig. 8, changes of T_c from ~2 to ~0.5 are observed in response to changes from α=0 to α=2. In case of Fig. 9, changes of T_c from ~1.6 to ~0.5 are observed in response to changes from α=0 to α=2. In case of Fig. 10, changes of T_c from ~1.3 to ~0.3 are observed in response to changes from α=0 to α=2. In any of these cases, phase transition temperatures as ferromagnetic materials are controlled in sufficiently wide temperature ranges by selecting values of α.

In regions where the fractal dimension is larger than 2.5, significantly sensitive changes in phase transition temperature are recognized. Therefore, by using fractal-coupled structures in these regions, efficient phase transition modulation is ensured.

A specific example of ferromagnetic fractal-coupled structure according to the first embodiment

is shown in Fig. 11. That is, as shown in Fig. 11, ferromagnetic material atoms 1 are placed on a substrate 2, and these atoms 1 are re-positioned in a fractal arrangement by using a needle 3 of, for example, a scanning tunneling microscope. When the distance between adjacent atoms 1 is sufficiently small, the atoms move to couple and the structure behaves as a magnetic material. This fractal-coupled structure of atoms 1 is a ferromagnetic fractal-coupled structure.

Next explained is the second embodiment of the invention. Explanation is made here about control of fractal-coupled structures added with magnetic impurities, which realize self-similar strong-coupled quantum chaos.

(1) Formation of a Fractal

Formation of a fractal follows (1) of the first embodiment. Figs. 12, 13 and 14 show treelike fractals obtained by n=10000 fractal growth under α=0, 1 and 2. Fig. 12 is that under α=0, Fig. 13 is that under α=1, and Fig. 14 is that under α=2. Fractal dimensions D_F of fractal patterns obtained by numerical simulation with various values of α are collectively shown in Fig. 15.

(2) Electron System on a Fractal

Let a quantum system of one particle be defined on the fractal defined in (1). Assume a lattice site shown below, which is the origin of T_n.

$$r_p = (i_{1,p}, i_{2,p}, i_{3,p}) \in T_n \qquad (14)$$

where p=1, 2, ..., n+1. An operator $\hat{c}_p^{\dagger}$ that creates a

quantum at a lattice site $r_p \in T_n$. Of course, an anticommutative relation

$$\left\{\hat{c}_p, \hat{c}_q^{\dagger}\right\} = \delta_{p,q} \tag{15}$$

is established. Here the Hamiltonian $\hat{H}$ is defined as

$$\hat{H}_n = -\sum_{p,q} t_{p,q} \hat{c}_p^{\dagger} \hat{c}_q \tag{16}$$

Here is employed as the transfer $t_{p,q}$,

$$t_{p,q} = \begin{cases} \exp(i\theta_{p,q}) & when \quad |r_p - r_q| = 1 \\ 0 & otherwise \end{cases} \tag{17}$$

where $\theta_{p,q}=-\theta_{q,p}$ is a random real number that satisfies

$$0 < \theta_{p,q} < 2\pi r \tag{18}$$

The fluctuation range is adjusted by r. In this model, hopping is possible only between nearest-neighbor sites. Along with the hopping, the random phase factor is replaced depending upon the sites. When the phase factor is integrated by a loop making a round of the lattice site, it results in a magnetic flux passing through the loop Locally, therefore, it results in introducing magnetic fields in the random distribution of $0<\theta_{p,q}<2\pi r$. This magnetic fields are absolutely random both in strength and in direction, and it is a zero magnetic field in spatial average. Therefore, it never breaks the fractal property of the system. Self-similarity of treelike fractals discussed in this section may be created through an inherently random process, and it exists in the spatial average range. Since the above-mentioned random magnetic fields disappear in terms of spatial average, it does not

break the self-similarity of the treelike fractal. Degeneracy in density of states due to self-similarity is not broken by random magnetic fields. In case of r=0, it results in a model where no random magnetic field exists.

When ε_m denotes the eigenenergy of the Hamiltonian $\hat{H}$ and $|m\rangle$ denotes the eigenvector,

$$\hat{H}|m\rangle = \varepsilon_m|m\rangle \tag{19}$$

where m=0, 1, 2, ..., n.

First, n+1 quantum levels ε_m are quantized such that spacing between nearest-neighbor levels becomes 1 in average. That is,

$$\omega_j = \varepsilon_j - \varepsilon_{j-1} \tag{20}$$

However, when j=1, 2, ..., n, by using

$$\overline{\omega} = \frac{1}{n}\sum_{j=1}^{n}\omega_j \tag{21}$$

it is converted into new levels

$$\varepsilon_0 = 0 \tag{22}$$

$$\varepsilon_m = \frac{1}{\overline{\omega}}\sum_{j=1}^{m}\omega_j = \sum_{j=1}^{m}\Omega_j \tag{23}$$

Here,

$$\Omega_j = \frac{\omega_j}{\overline{\omega}} \tag{24}$$

The density of states of the system is defined by

$$\rho(\varepsilon) = \frac{1}{n+1}\sum_{m=1}^{n+1}\delta(\varepsilon - \varepsilon_m) \tag{25}$$

the staircase function

$$\lambda(\varepsilon) = \int_{-\infty}^{\varepsilon} d\eta \rho(\eta) \tag{26}$$

is calculated. The staircase function obtained is converted by "unfolding" such that the density of states becomes constant in average. By using quantum levels obtained in this manner, nearest-neighbor level spacing distribution P(s) and Δ_3 statistics of Dyson and Metha are calculated as quantum level statistics. As taught in a literature ((37) L.E. Reichl, The transition to chaos: in conservative classical systems: quantum manifestations (Springer, New York, 1992); (38) F. Haake, Quantum Signatures of chaos, (Springer-Verlag, 1991)), by using these statistics, it can be detected whether quantum chaos has been generated or not. It is also known that a quantum chaotic system is sensitive to perturbation from outside similarly to the classical chaotic system, and analysis of quantum chaos is important as a polestar of designs of non-linear materials.

In case of an integrable system, nearest-neighbor level spacing distribution P(s) and Δ_3 statistics of Dyson and Metha are those of Poisson Distribution

$$P_P(s) = e^{-s} \tag{27}$$

$$\Delta_3(n) = \frac{n}{15} \tag{28}$$

In a system obeying GOE distribution that is the weakest quantum chaos, they are

$$P_{GOE}(s) = \frac{\pi s}{2} e^{-\pi s^2/4} \tag{29}$$

$$\Delta_3(n) = \frac{1}{\pi^2}\left[\log(2\pi n) + \gamma - \frac{\pi^2}{8} - \frac{5}{4}\right] + O(s^{-1}) \tag{30}$$

where γ is the Euler's constant. Figs. 16 and 17 show quantum level statistics under r=0. As α becomes smaller, transition occurs from Poisson distribution to GEO distribution. In a treelike fractal with no magnetic impurities, quantum chaos that appears under small values of α is characterized by GOE distribution. Regions with s~0 of P(s) should be remarked. In integrable systems, P(s)~1. On the other hand, in case of GOE distribution, P(s)~$\propto$, and in regions of s~0, probability of existence of level spacing is proportional to the energy difference s.

On the other hand, statistics under r=1 with magnetic impurities in the second embodiment are shown in Figs. 18 and 19. As α decreases, transition occurs from Poisson distribution to GUE (Gaussian unitary ensemble). In this GUE distribution,

$$P_{GUE}(s) = \frac{32 s^2}{\pi^2} e^{-4s^2/\pi} \tag{31}$$

$$\Delta_3(n) = \frac{1}{2\pi^2}\left[\log(2\pi n) + \gamma - \frac{5}{4}\right] + O(s^{-1}) \tag{32}$$

That is, in regions of s~0, P(s)$\propto s^2$, values of P(s) are suppressed more strongly. Therefore, by introducing magnetic impurities, it has been found that stronger quantum chaos characterized by GUE distribution appears.

Through such strong quantum chaos, Anderson transition can be controlled in fractal-coupled structures added with magnetic impurities.

Examples of fractal-coupled structures added with magnetic impurities include fractal-coupled structure made of Cu and doped with Mn as the magnetic impurity, fractal-coupled structures made of GaAs and doped with Mn as the magnetic impurity, and so on. Magnetic impurities to be doped are, in general, those with an impurity level not overlapping the bulk quantum level.

Next explained is the third embodiment of the invention. As the third embodiment, control of Mott-Hubbard transition by fractal dimensions of fractal-coupled structures is explained.

Fractal-coupled structures are made by creating fractals as explained below, and defining electron systems thereon.

(1) Formation of a Fractal

Formation of a fractal follows (1) of the first embodiment. Figs. 12, 13 and 14 show treelike fractals obtained by n=10000 fractal growth under α=0, 1 and 2. Fig. 12 is that under α=0, Fig. 13 is that under α=1, and Fig. 14 is that under α=2. Fractal dimensions D_f of fractal patterns obtained by numerical simulation with various values of α are collectively shown in Fig. 15.

(2) Electron System on a Fractal

An electron system is defined on the fractal

defined in (1). Assume a lattice site shown below, which is the origin of T_n.

$$r_p = (i_{1,p}, i_{2,p}, i_{3,p}) \in T_n \tag{33}$$

where p=1, 2, ..., n+1. An operator $\hat{c}^{\dagger}_{p,q}$ that creates an electron of a spin σ at a lattice site $r_p \in T_n$. Of course, an anticommutative relation

$$\{\hat{c}_{p,\sigma}, \hat{c}^{\dagger}_{q,\rho}\} = \delta_{p,q}\delta_{\sigma,\rho} \tag{34}$$

is established. Here the single-band Hubbard Hamiltonian $\hat{H}$ is defined as

$$\hat{H} = t\sum_{i,j,\sigma}\lambda_{i,j}\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + U\sum_{j}\hat{n}_{j,\uparrow}\hat{n}_{j,\downarrow} \tag{35}$$

Let electrons be movable only among nearest-neighbor sites, and the following is employed as $\lambda_{p,q}$.

$$\lambda_{p,q} = \begin{cases} 1 & when \quad |r_p - r_q| = 1 \\ 0 & otherwise \end{cases} \tag{36}$$

Additionally, the spin σ electron density operator of the j-th site, $\hat{n}_{j,\sigma} = \hat{c}^{\dagger}_{j,\sigma}\hat{c}_{j,\sigma}$, and their sum, $\hat{n}_j = \sum_{\sigma}\hat{n}_{j,\sigma}$ are defined.

To define the temperature Green function, the Taisho quasi-Hamiltonian $\hat{K} = \hat{H} - \mu\hat{N}$ is introduced, where $\hat{N} = \sum_j \hat{n}_j$. In the half filled taken here, chemical potential is μ=U/2. The half-filled grand-canonical Hamiltonian can be expressed as

$$\hat{K} = t\sum_{i,j,\sigma}\lambda_{j,i}\hat{t}_{j,i,\sigma} + U/2\sum_{i}(\hat{u}_i - 1) \tag{37}$$

Operators $\hat{t}_{j,i,\sigma}$, $\hat{j}_{j,i,\sigma}$, $\hat{u}_i$ and $\hat{d}_{i,\sigma}$ are previously defined as

$$\hat{t}_{j,i,\sigma} = \hat{c}^{\dagger}_{j,\sigma}\hat{c}_{i,\sigma} + \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} \tag{38}$$

$$\hat{j}_{j,i,\sigma} = \hat{c}^{\dagger}_{j,q}\hat{c}_{i,\sigma} - \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} \tag{39}$$

$$\hat{u}_i = \hat{c}^{\dagger}_{i,\uparrow}\hat{c}_{i,\uparrow}\hat{c}^{\dagger}_{i,\downarrow}\hat{c}_{i,\downarrow} + \hat{c}_{i,\uparrow}\hat{c}^{\dagger}_{i,\uparrow}\hat{c}_{i,\downarrow}\hat{c}^{\dagger}_{i,\downarrow} \tag{40}$$

$$\hat{d}_{i,\sigma} = \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i,\sigma} - \hat{c}_{i,\sigma}\hat{c}^{\dagger}_{i,\sigma} \tag{41}$$

If the temperature Green function is defined for operators $\hat{A}$ and $\hat{B}$ given, taking τ as imaginary time, it is as follows.

$$\left\langle \hat{A};\hat{B} \right\rangle = -\int_0^{\beta} d\tau \left\langle T_{\tau}\hat{A}(\tau)\hat{B} \right\rangle e^{i\omega_n \tau} \tag{42}$$

The on-site Green function

$$G_{j,\sigma}(i\omega_n) = \left\langle \hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma} \right\rangle \tag{43}$$

is especially important because analytic continuation $i\omega_n \rightarrow \omega + i\delta$ for a small δ results in

$$-\sum_{\sigma=\uparrow,\downarrow} \mathrm{Im} G_{j,\sigma}(\omega + i\delta) \tag{44}$$

as the local density of states of the site j, and

$$-\frac{1}{n+1}\sum_{j,\sigma} \mathrm{Im} G_{j,\sigma}(\omega + i\delta) \tag{45}$$

as the density of states of the system. For later numerical calculation of densities of states, δ=0.0001 will be used.

Imaginary time development of the system is obtained by the Heisenberg equation

$$\frac{d}{d\tau}\hat{A}(r) = \left[\hat{K},\hat{A}\right] \tag{46}$$

As the equation of motion of the on-site Green function,

$$i\omega_n\left\langle \hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle = 1 + t\sum_{p,j}\lambda_{p,i}\left\langle \hat{c}_{p,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle + \frac{U}{2}\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \quad (47)$$

is obtained. Then, the approximation shown below is introduced, following Gros ((39) C. Gros, Phys. Rev. B50, 7295(1994)). If the site p is the nearest-neighbor site of the site j, the resolution

$$\left\langle \hat{c}_{p,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \to t\left\langle \hat{c}_{p,\sigma};\hat{c}^{\dagger}_{p,\sigma}\right\rangle\left\langle \hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \quad (48)$$

is introduced as the approximation. This is said to be exact in case of infinite-dimensional Bethe lattices, but in our case, it is only within approximation. Under the approximation, the following equation is obtained.

$$(i\omega_n - t^2\Gamma_{j,\sigma})G_{j,\sigma} = 1 + \frac{U}{2}\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \quad (49)$$

where

$$\Gamma_{j,\sigma} = \sum_{p}\lambda_{p,j}G_{p,\sigma} \quad (50)$$

was introduced. To solve the equation obtained, $\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle$ has to be analyzed. In case of a half-filled electron density, this equation of motion is

$$i\omega_n\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle = \frac{U}{2}G_{j,\sigma} - 2t\sum_{p}\lambda_{p,j}\left\langle \hat{j}_{p,j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle$$

$$+ t\sum_{p}\lambda_{p,j}\left\langle \hat{d}_{j,-\sigma}\hat{c}_{p,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \quad (51)$$

Here again, with reference to the Gros logic, approximation is introduced. It is the following translation.

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$$\left\langle \hat{j}_{p,j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \rightarrow -tG_{p,-\sigma}\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \qquad (52)$$

$$\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \rightarrow tG_{p,\sigma}\left\langle \hat{d}_{j,-\sigma}\hat{c}_{j,\sigma};\hat{c}^{\dagger}_{j,\sigma}\right\rangle \qquad (53)$$

By executing this translation, the following closed equation was obtained.

$$\left(i\omega_n - t^2\Gamma_{j,\sigma}\right)G_{j,\sigma} = 1 + \frac{(U/2)^2}{i\omega_n - t^2\Gamma_{j,\sigma} - 2t^2\Gamma_{j,-\sigma}}G_{j,\sigma} \qquad (54)$$

assuming that it is under no dependency on spin. That is, assuming $G_{j,\uparrow}=G_{j,\downarrow}$, the following calculation is executed.

Fig. 20 shows densities of states obtained by numerical calculation. n=10000 sites were used as a treelike fractal. In this calculation, t=1 and U=12 were used under α=0, 1, 2. The band are separated into right and left sides, and the left side is the lower Hubbard band whereas the right side is the upper Hubbard band. Only the lower Hubbard band is filled with electrons, and the region between right left sides with zero density of states is the Mott-Hubbard gap. Fig. 21 shows the region near the Mott-Hubbard gap in an enlarged scale. It is appreciated that, as α increases (as the fractal dimension decreases), the Mott-Hubbard gap increases, and insulation is enhanced. Regarding Mott transition caused by changes of U, densities of states are shown. Fig. 22 shows those by changes of U=4, 8, 12, 16 under t=1 and α=1. Peaks of densities of states in the center of the subband are those by degeneracy of states caused y fractal properties.

Fig. 23 shows those by changes of U=2, 4, 8, 16 under fixed α=1, as examples of densities of states obtained by numerical calculations under fixed t=1 and n=10000. Fig. 24 shows results with a three-dimensional ball (3D-ball) of 10001 sites under U=8 and α=0, 1, 2. Fig. 25 shows Hubbard gaps plotted by continuously changing U under α=0, 0.2, 0.4, 0.6, 1.2. Fig. 26 shows densities of states in terms of Fermi energy, plotted by continuously changing U here again under α=0, 0.2, 0.4, 0.6, 1.2. In critical interaction of electrons U_c where Mott transition occurs, it is appreciated that Hubbard gaps appear and densities of states in terms of Fermi energy disappear. Then, the critical value U_c is controlled by α.

Examples of fractal-coupled structured adjusted to half-filled electron densities include fractal-coupled structures made of monatomic metals, fractal-coupled structures made of V_2O_3, and so forth.

Fractal-coupled structures adjusted in half-filled electron densities may be made of quantum dot arrays by heterojunction of compound semiconductors. One of such examples is shown in Figs. 28A and 28B. Fig. 28A is a cross-sectional view and Fig. 28B is a plan view illustrating placement of the quantum dot array.

As shown in Figs. 28A and 28B, this fractal-coupled structure contains a fractal arrangement of GaAs quantum dots 11 of i-type GaAs, which are confined by i-type AlGaAs 12. The quantum dot array of GaAs quantum dots 11 is adapted

to allow tunneling of electrons between nearest-neighbor quantum dots.

Heretofore, specific examples according to embodiments of the invention have been explained. However, the invention is not limited to those embodiments, but should be interpreted to involve various modifications based on the technical concept of the invention.

As described above, according to the invention, by controlling fractal dimensions of fractal-coupled structures overall or locally, phase transition can be controlled without the need for heating. Then, such phase transition can be used in information storage, or more generally, information processing.

CLAIMS

1. A method for controlling phase transition of a fractal-coupled structure characterized in controlling phase transition by controlling fractal dimension of a fractal-coupled structure overall or locally.

2. The method for controlling phase transition of a fractal-coupled structure according to claim 1 wherein phase transition temperature is controlled by controlling fractal dimension of said fractal-coupled structure.

3. The method for controlling phase transition of a fractal-coupled structure according to claim 1 wherein said fractal-coupled structure is a ferromagnetic fractal-coupled structure and ferromagnetic phase transition temperature is controlled by controlling fractal dimension of said ferromagnetic fractal-coupled structure.

4. The method for controlling phase transition of a fractal-coupled structure according to claim 1 wherein said fractal-coupled structure is a ferromagnetic fractal-coupled structure whose dimension is not smaller than 2.5.

5. The method for controlling phase transition of a fractal-coupled structure according to claim 1 wherein generation of quantum chaos in said fractal-coupled structure is controlled by controlling fractal dimension of said fractal-coupled structure.

6. The method for controlling phase transition of

a fractal-coupled structure according to claim 5 wherein said fractal-coupled structure is a fractal-coupled structure added with a magnetic impurity.

7. The method for controlling phase transition of a fractal-coupled structure according to claim 5 wherein said phase transition is Anderson transition.

8. The method for controlling phase transition of a fractal-coupled structure according to claim 1 wherein said phase transition is metal-insulator transition.

9. The method for controlling phase transition of a fractal-coupled structure according to claim 8 wherein said fractal-coupled structure is controlled to exhibit a half-filled electron density.

10. The method for controlling phase transition of a fractal-coupled structure according to claim 8 wherein said fractal-coupled structure is composed of an array of quantum dots.

11. The method for controlling phase transition of a fractal-coupled structure according to claim 10 wherein said quantum dots are made of heterojunction of compound semiconductors.

12. A ferromagnetic fractal-coupled structure characterized in comprising a magnetic material configured to have self-similarity.

13. The ferromagnetic fractal-coupled structure according to claim 12 wherein ferromagnetic phase transition temperature is determined by selection of fractal dimension

that characterizes the self-similarity of said magnetic material.

14. The ferromagnetic fractal-coupled structure according to claim 12 wherein said fractal dimension of said magnetic material is not smaller than 2.5.

15. A fractal-coupled structure characterized in being configured to have self-similarity and being applied with random magnetic fields.

16. The ferromagnetic fractal-coupled structure according to claim 15 wherein said random magnetic fields are applied by adding a magnetic impurity to the component material.

17. A fractal-coupled structure characterized in being configured to have self-similarity and having a half-filled electron density.

18. The ferromagnetic fractal-coupled structure according to claim 17 wherein interaction of electrons in an electron system can be increased larger than the band with, and Mott transition exists, said Mott transition being controlled by fractal dimension of the system.

19. The ferromagnetic fractal-coupled structure according to claim 17 wherein said fractal-coupled structure is composed of an array of quantum dots made of heterojunction of compound semiconductors.

20. The ferromagnetic fractal-coupled structure according to claim wherein said fractal-coupled structure forms a semiconductor device or an electronic device.

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21. An information processing method characterized in executing information processing by controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

22. An information storage method characterized in performing information storage by controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

23. The information storage method according to claim 22 wherein many-value information storage is performed.

24. An information storage medium using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity.

25. The information storage medium according to claim 24 capable of many-value information storage.

26. An information storage medium using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields.

27. The information storage medium according to claim 26 using coexistence of degeneracy of density of states caused by the self-similarity and a strong quantum chaotic state, which appear in said fractal-coupled structure.

28. An information storage medium characterized in using a fractal-coupled structure which is configured to have self-similarity and has a half-filled electron density.

29. An information processing device characterized in executing information processing by controlling phase

transition through overall or local control of fractal dimension of a fractal-coupled structure.

30. An information processing device characterized in:

using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity; and

executing information processing by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

31. An information processing device characterized in:

using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields; and

executing information processing by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

32. An information processing device characterized in:

using a fractal-coupled structure configured to have self-similarity and having a half-filled electron state; and

executing information processing by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

33. An information storage device characterized in

executing information storage by controlling phase transition through overall or local control of fractal dimension of a fractal-coupled structure.

34. An information storage device characterized in:

using a ferromagnetic fractal-coupled structure made of a magnetic material configured to have self-similarity; and

executing information storage by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

35. An information storage device characterized in:

using a fractal-coupled structure configured to have self-similarity and applied with random magnetic fields; and

executing information storage by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

36. An information storage device characterized in:

using a fractal-coupled structure configured to have self-similarity and having a half-filled electron density; and

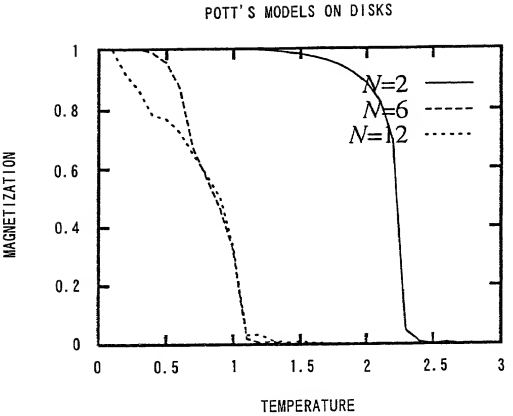
executing information storage by controlling phase transition through overall or local control of fractal dimension of said fractal-coupled structure.

Fig. 1

α	D_f
0.0	2.91
0.4	2.79
0.8	2.54
1.2	2.25
1.6	2.21
2.0	2.16

09868360.010302

Fig. 2



2001-0103502-0068850

Fig. 3

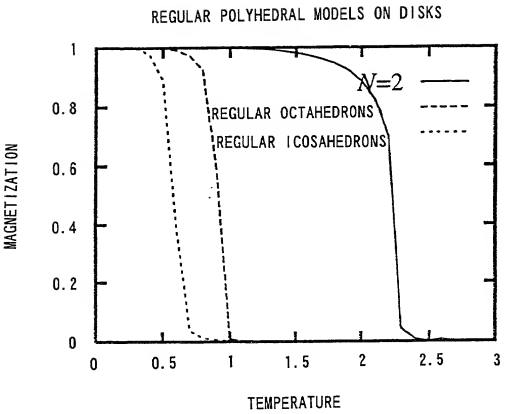


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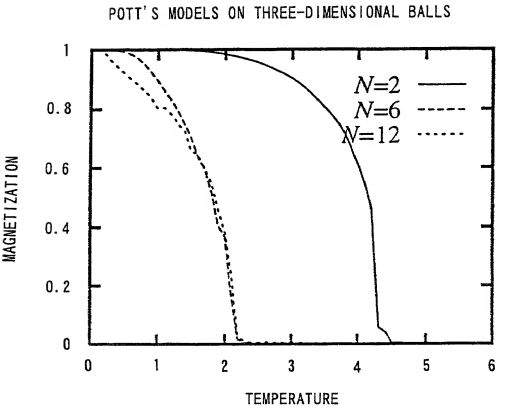
Fig. 4



20010130.0100202

Fig. 5

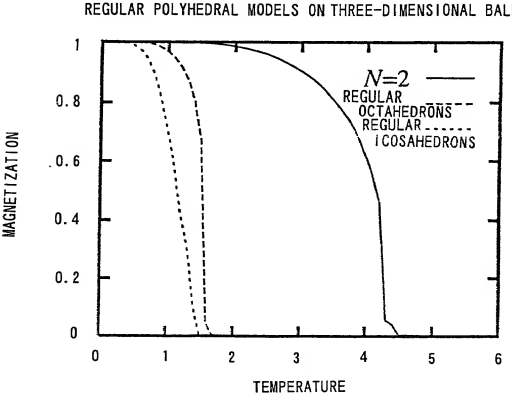
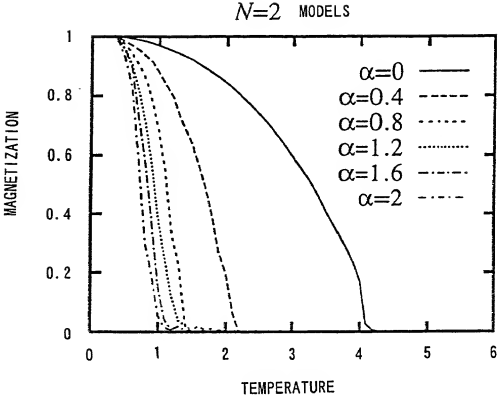

REGULAR POLYHEDRAL MODELS ON THREE-DIMENSIONAL BALLS
MAGNETIZATION
TEMPERATURE
N=2
REGULAR OCTAHEDRONS
REGULAR ICOSAHEDRONS
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6

Fig. 6



20010"09868360

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Fig. 7

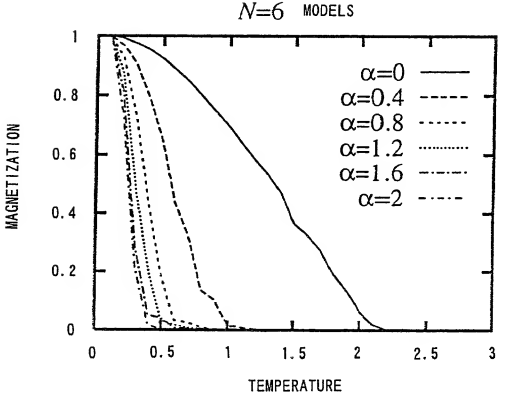
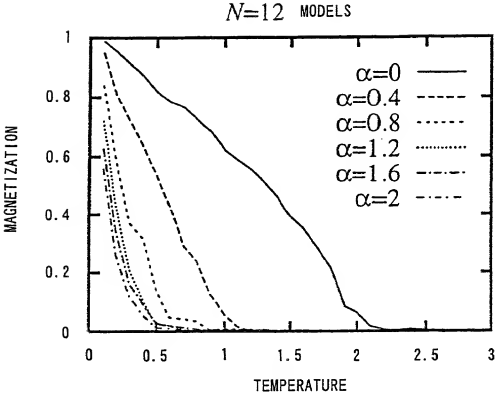
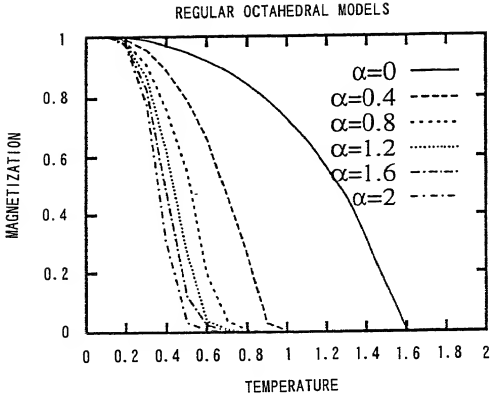


Fig. 8



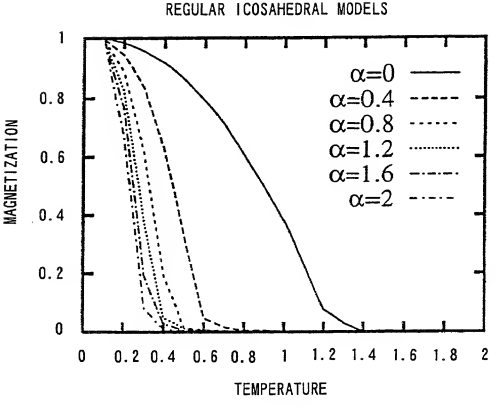
20010109.0898360

Fig. 9



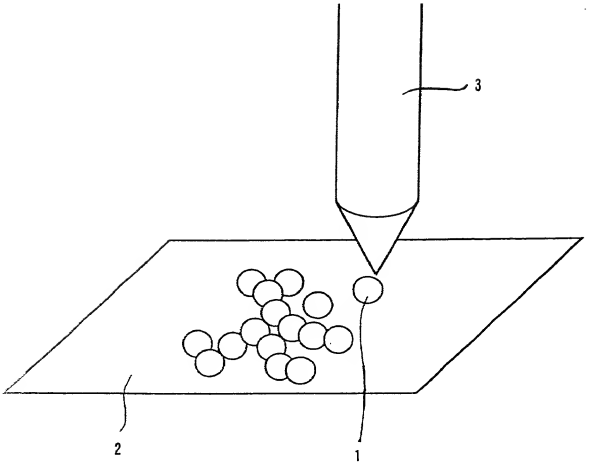
20020104.09868360

Fig. 10



09868360.010302

Fig. 11



20010302.0350/9860

Fig. 12

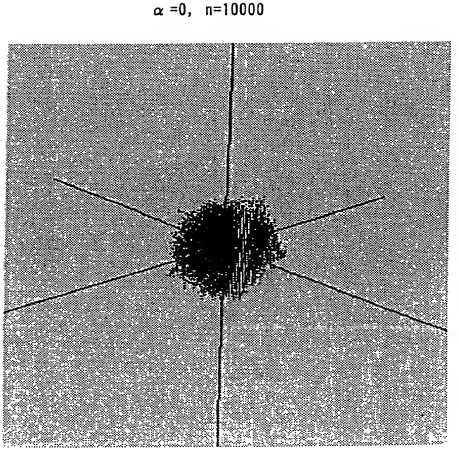


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Fig. 13

09868360.010202

α=1, n=10000

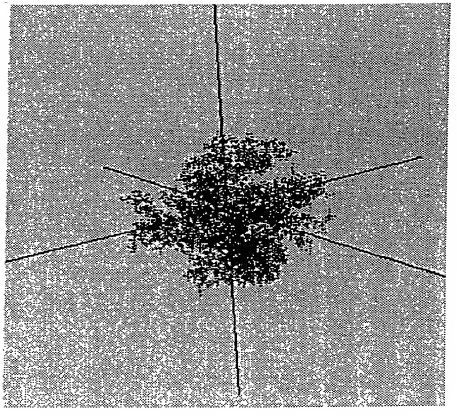
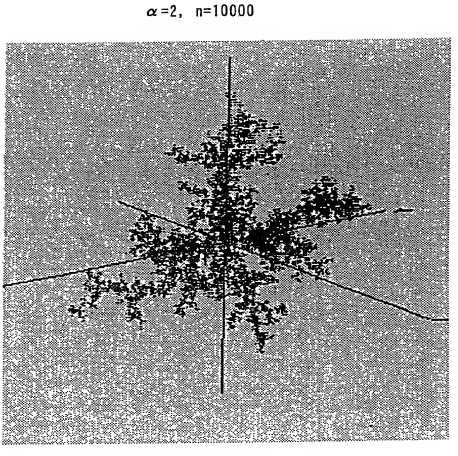


Fig. 14



09868360.010302

Fig. 15

α	D_f
0.0	2.910
0.2	2.897
0.4	2.790
0.6	2.577
1.0	2.450
2.0	2.164

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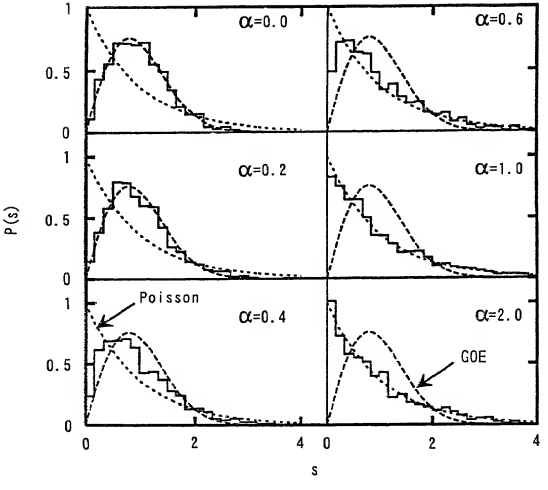
Fig. 16



20010109.0858360

Fig. 17

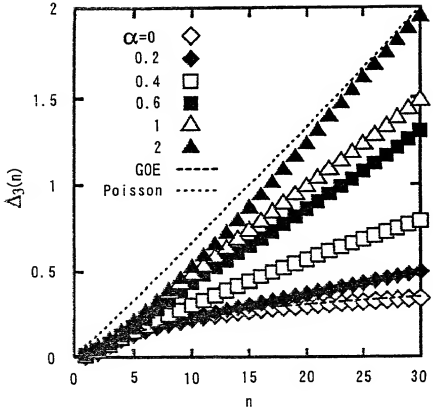


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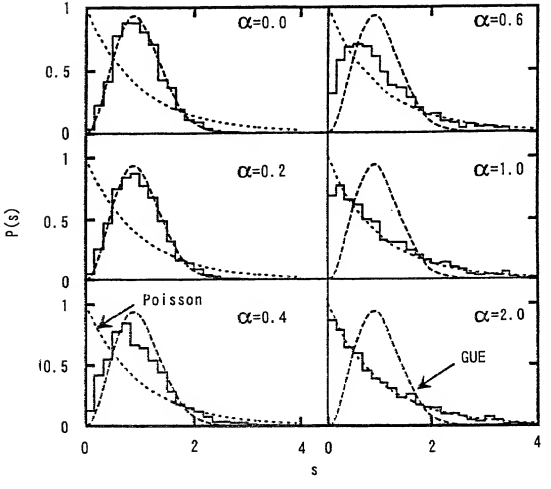
Fig. 18



20030102.0988360

Fig. 19

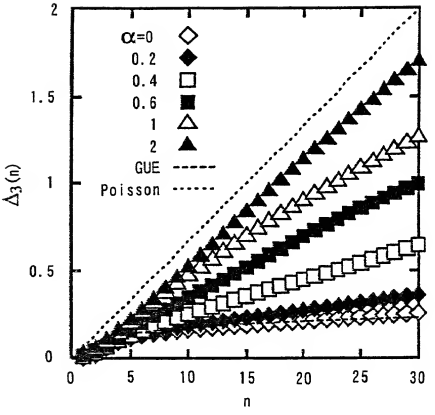


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Fig. 20

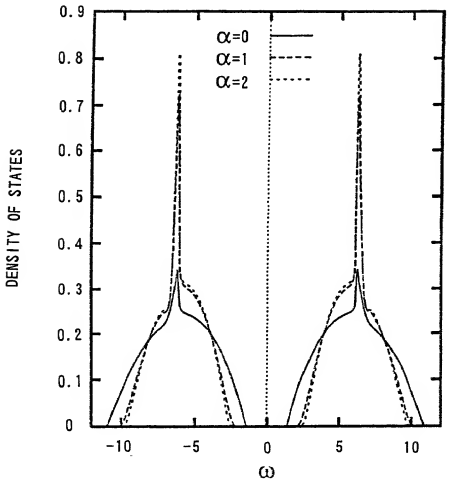

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Fig. 21

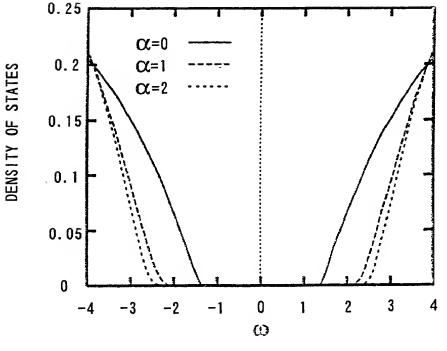

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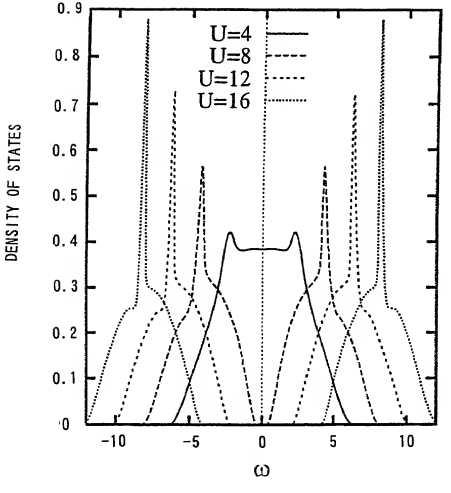
Fig. 22



20010709C89860

Fig. 23

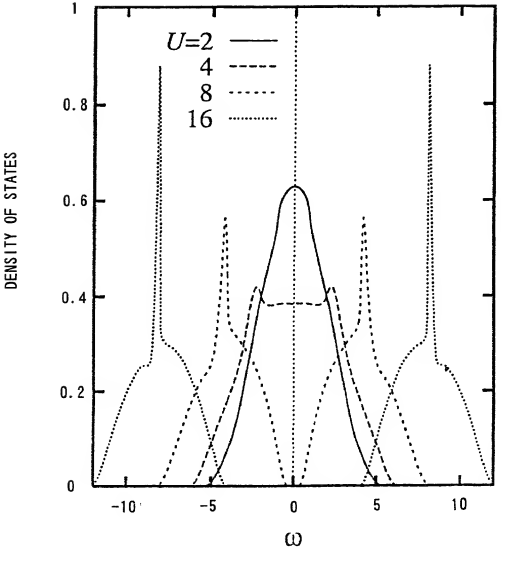
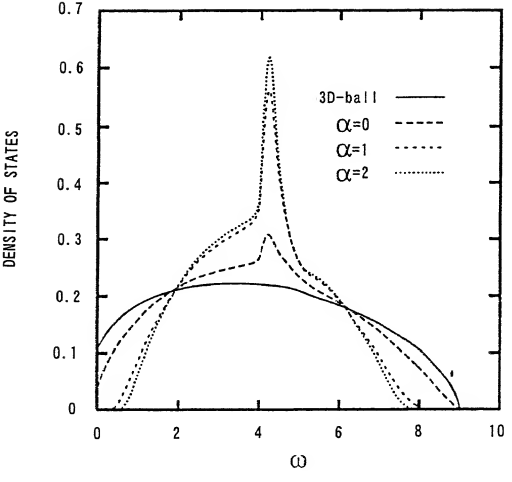
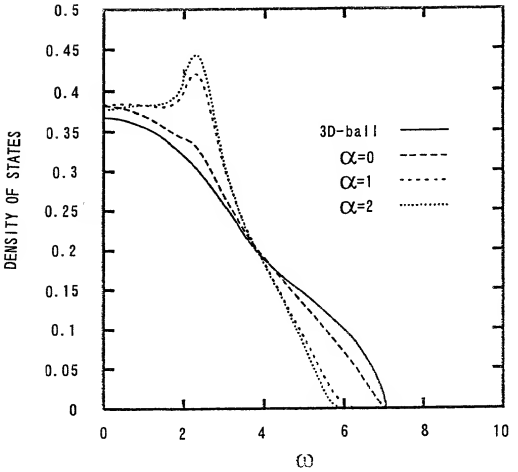


Fig. 24



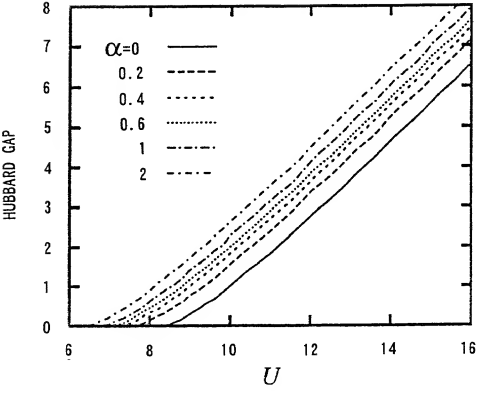
20020104.0868360

Fig. 25



09868360.010202

Fig. **26**



09868360.010302

Fig. 27

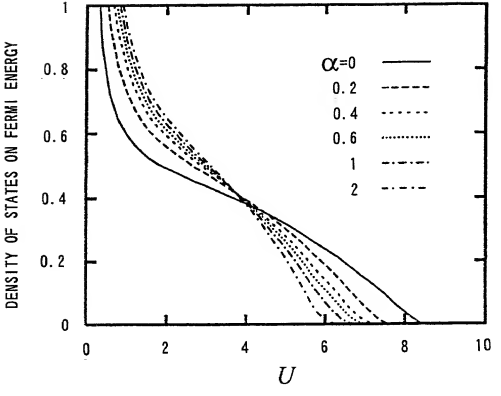


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Fig. 28A

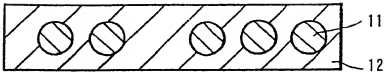
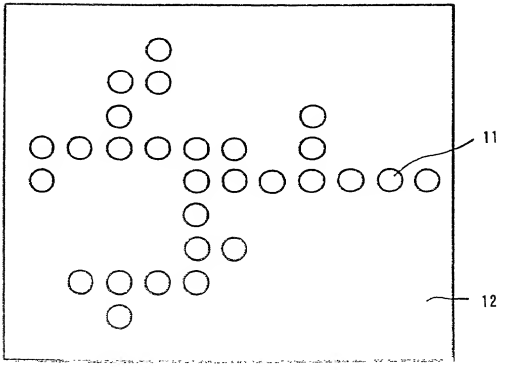


Fig. 28B



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09868360.010302

1	ATOMS OF A FERROMAGNETIC MATERIAL
2	SUBSTRATE
3	NEEDLE
11	GaAs QUANTUM DOTS
12	i-TYPE AlGaAs

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION
特許出願宣言書及び委任状

Japanese Language Declaration

日本語宣言書

ATTORNEY DOCKET NO. 09794353-0008
(inadvertently submitted as 09794353-0016)

下記の氏名の発明者として、私は以下の通り宣言します。

As a below named inventor, I hereby declare that:

私の住所、私書箱、国籍は下記の私の氏名の後に記載された通りです。

My residence, post office address and citizenship are as stated next to my name,

下記の名称の発明に関して請求範囲に記載され、特許出願している発明内容について、私が最初かつ唯一の発明者（下記の氏名が一つの場合）もしくは最初かつ共同発明者であると（下記の名称が複数の場合）信じています。

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

"CONTROL METHOD OF PHASE TRANSITION OF FRACTAL-COUPLED STRUCTURE, FRACTAL-COUPLED STRUCTURE, FERROMAGNETIC FRACTAL-COUPLED STRUCTURE, INFORMATION PROCESSING METHOD, INFORMATION STORAGE METHOD, INFORMATION STORAGE MEDIUM, INFORMATION PROCESSING DEVICE AND INFORMATION STORAGE DEVICE"

上記発明の明細書（下記の欄でx印がついていない場合は、本書に添付）は、

the specification of which is attached hereto unless the following box is checked:

☐ __月__日に提出され、米国出願番号または特許協定条約国際出願番号を_____とし、
（該当する場合）_____ に訂正されました。

■ was filed on October 17, 2000 as **United States Application Number** or PCT International Application Number PCT/JP00/07182 and filed as U.S. Application Serial No. 09/868,360 filed on June 15, 2001, and was amended on June 15, 2001, (if applicable)

私は、特許請求範囲を含む上記訂正後の明細書を検討し、内容を理解していることをここに表明します。

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

私は、連邦規則法典第３７編第１条５６項に定義されるとおり、特許資格の有無について重要な情報を開示する義務があることを認めます。

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

私は、米国法典第３５編１１９条(a)-(d)項又は３６５条(b)項に基き下記の、米国以外の国の少なくとも一ヵ国を指定している特許協力条約３６５(a)項に基ずく国際出願、又は外国での特許出願もしくは発明者証の出願についての外国優先権をここに主張するとともに、優先権を主張している、本出願の前に出願された特許または発明者証の外国出願を以下に、枠内をマークすることで、示しています。

I hereby claim foreign priority under Title 35, United States Code, Section 119(a)-(d) or 365(b) of any foreign application(s) for patent or Inventor's certificate or 365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or Inventor's certificate or PCT International application having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)
外国での先行出願

JP1999-298810 Japan Oct. 20, 1999

(Number) (Country) (Day Month Year Filed)
(番号) (国名) (出願年月日)

(Number) (Country) (Day Month Year Filed)
(番号) (国名) (出願年月日)

Priority Not Claimed
優先権主張なし

(Number) (Country) (Day Month Year Filed)

(Number) (Country) (Day Month Year Filed)

私は、第３５編米国法典１１９条(e)項に基いて下記の米国特許出願規定に記載された権利をここに主張いたします。

I hereby claim the benefit under Title 35, United States Code, Section 119(e) of any United States provisional application(s) listed below.

(Application No.) (Filing Date)
(出願番号) (出願日)

(Application No.) (Filing Date)
(出願番号) (出願日)

私は、下記の米国法典第３５編１２０条に基いて下記の米国特許出願に記載された権利、又は米国を指定している特許協力条約３６５条(c)に基ずく権利をここに主張します。また、本出願の各請求範囲の内容が米国法典第３５編１１２条第１項又は特許協力条約で規定された方法で先行する米国特許出願に開示されていない限り、その先行米国出願書提出日以降で本出願書の日本国内または特許協力条約国際提出日までの期間中に入手された、連邦規則法典第３７編１条５６項で定義された特許資格の有無に関する重要な情報について開示義務があることを認識しています。

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) or 365(c) of an PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

Japanese Language Declaration

(日本語宣言書)

(Application No.) (出願番号)	(Filing Date) (出願日)	(Status: patented, pending, abandoned) (現況：特許許可済、係属中、放棄済)
(Application No.) (出願番号)	(Filing Date) (出願日)	(Status: patented, pending, abandoned) (現況：特許許可済、係属中、放棄済)

私は、私自身の知識に基ずいて本宣言書中で私が行なう表明が真実であり、かつ私の入手した情報と私の信じるところに基ずく表明が全て真実であると信じていること、さらに故意になされた虚偽の表明及びそれと同等の行為は米国法典第１８編第１００１条に基ずき、罰金または拘禁、もしくはその両方により処罰されること、そしてそのような故意による虚偽の声明を行なえば、出願した、又は既に許可された特許の有効性が失われることを認識し、よってここに上記のごとく宣言を致します。

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

委任状：　私は下記の発明者として、本出願に関する一切の手続きを米特許商標局に対して遂行する弁理士または代理人として、下記の者を指名いたします。（弁護士、または代理人の氏名及び登録番号を明記のこと）

POWER OF ATTORNEY: As a named Inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. (list name and registration number)

David R. Metzger (Reg. No. 32,919), Joseph A. Mahoney (Reg. No. 38,956), Howard B. Rockman (Reg. No. 22,190), Jordan A. Sigale, (Reg. No. 39,028), Michael A. Molano (Reg. No. 39,777), Michael L. Kiklis (Reg. No. 38,939), Janelle D. Strode (Reg. No. 34,738), Kevin W. Guynn (Reg. No. 29,972), Jennifer Hammond (Reg. No. 41,814), Lana Knedlik (Reg. No. 42,748), John F. Griffith (Reg. No. 44,137), Marina Saito (Reg. No. 42,121), Alison P. Schwartz (Reg. No. 43,863), Christopher P. Rauch (Reg. No. 45,034), Francisco Rubio-Campos (Reg. No. 45,358), Brian J. Gill (Reg. No. 46,727) and Shashank S. Upadbye, all members of the firm of Sonnenschein, Nath & Rosenthal

Send Correspondence to:

書類送付先

David R. Metzger
Sonnenschein Nath & Rosenthal
P.O. Box #061080
Wacker Drive Station
Chicago, Illinois 60606-1080

直接電話連絡先：（名前及び電話番号）　Direct Telephone Calls to: (name and telephone number)

312/876-2578

Japanese Language Declaration

(日本語宣言書)

0500.0400

唯一または第一発明者名	Full name of sole or first inventor: RYUICHI UGAJIN
発明者の署名　日付	Inventor's signature　Date Ryuichi Ugajin　10 Oct. 2001
住所	Residence Japan
国籍	Citizenship Japan
私書箱	Post Office Address c/o Sony Corporation 7-35, Kitashinagawa 6-chome
	Shinagawa-ku, Tokyo 141-0001, Japan JPX

（第三以降の共同発明者についても同様に記載し、署名をすること）

第二共同発明者	Full name of second joint inventor, if any: YOSHIHIKO KUROKI
発明者の署名　日付	Inventor's signature　Date Yoshihiko Kuroki　11 Oct. 2001
住所	Residence Japan
国籍	Citizenship Japan
私書箱	Post Office Address c/o Sony Corporation 7-35, Kitashinagawa 6-chome
	Shinagawa-ku, Tokyo 141-0001, Japan JPX
第二共同発明者	Full name of third joint inventor, if any: MASAKAZU UKITA
発明者の署名　日付	Inventor's signature　Date Masakazu Ukita　16 Oct. 2001
住所	Residence Japan
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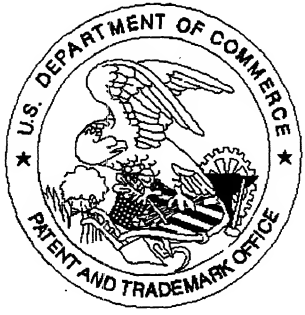

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